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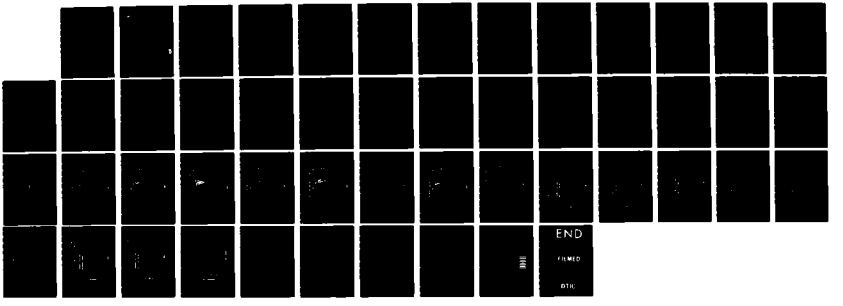

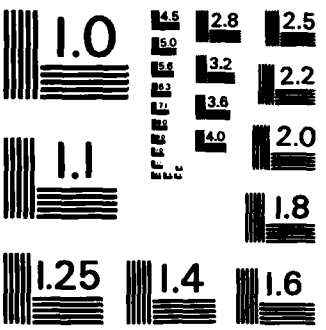

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MEMORANDUM REPORT BRL-MR-3451

WAVE MOTION ANALYSIS OF A NON-SPINNING LIQUID FILLED CYLINDER

Paul Weinacht
Charles J. Nietubicz

June 1985

US ARMY BALLISTIC RESEARCH LABORATORY
ABERDEEN PROVING GROUND, MARYLAND

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The results of a wave motion analysis of a partially liquid-filled, non-spinning cylinder are described. The analysis was undertaken to determine the internal fluid motion of a partially liquid-filled shell when subjected to large impulsive pressures. The high pressure levels are formed from the rupture of an internal burster tube. The primary concern is the determination of the endwall and side wall pressure levels after the burster tube rupture. The final objective of this program is to develop a predictive capability which can be used for

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20. ABSTRACT (Continued)

determining the effects of various liquids, ullages and burster pressure levels. This report describes an initial analysis of the fluid motion inside a partially liquid-filled, non-spinning cylinder subject to a large impulsive pressure at one end. The analysis presented, tracks the pressure wave motion as a function of time and uses conservation of mass and momentum principles to determine the fluid properties in front of and behind the pressure waves. The results show the effect of initial pressure level and ullage on the resulting end wall and side wall pressures as a function of time. The peak end wall pressure is found to vary directly with the initial pressure level. The time duration of the maximum pressure acting on the end wall is a strong function of the ullage and to a lesser degree on the bulk modulus of the liquid.

Compressible liquids; Wave motion analysis; Fluid mechanics.

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I. INTRODUCTION

The forced liquid project is being directed by the Munitions Branch of CRDC. The present task is to determine the internal reaction of a partially, liquid-filled shell subjected to large impulsive pressures from burster tube rupture. The main area of concern is the determination of the end wall and side wall pressures due to the sudden application of pressure at one end. A final objective is the development of a predictive capability which can be used to analyze the internal flow and quantify the internal pressure levels based on various liquids, ullages, and initial pressures.

II. GOVERNING EQUATIONS

The prediction of the fluid motion within a liquid-filled shell after a burster tube breaks is complicated by such factors as non-uniform geometry inside the shell, burster fragments, gas-liquid interaction, and release of pressure from the burster tube which may not remain at a constant level over the duration of the event. However, much of the basic physics which occurs inside the shell may be highlighted by examining the following highly simplified problem.

A cylindrical container of length, H, is filled with a fluid to a height L. The fluid is characterized by a density, ρ, and a bulk modulus, E. The portion of the container not occupied by fluid, the ullage, is assumed to be vacuum. Initiation of the event occurs with the application of a pressure step of magnitude, Po, applied to the lower surface of the fluid (see Figure 1). This pressure step generates a compression wave which propagates up the fluid slug. The ensuing fluid motion, which is assumed to occur isothermally, may be predicted by applying the equations of mass and momentum conservation across the pressure wave. A control volume, such as that shown in Figure 2, is fixed to move with the pressure wave at the speed of sound, c. Denoting the properties in front of the wave by the subscript 1 and properties behind the wave by 2, the mass and momentum equations are written below in terms of the pressure, P, density, ρ, fluid velocity, V, and wave speed, c.

Continuity

$$\rho_1 c = \rho_2 (c + V_1 - V_2) \tag{1}$$

Momentum

$$P_1 - P_2 = c^2 \rho_1 - (c + V_1 - V_2)^2 \rho_2 \tag{2}$$

An equation of state of the fluid is also required for the solution of these equations. In this analysis a simple equation of state is used.

$$\partial P / \partial \rho = E / \rho \tag{3}$$

Since the properties in front of the wave are known, one additional equation is required in order to solve for the four unknowns of interest; the wave speed, and the fluid pressure, density, and velocity behind the wave. This additional equation is, in a sense, a boundary condition, and is dependent on the manner in which pressure waves are generated or reflected at the fluid boundaries.

For a wave generated by a change in pressure at a boundary, the pressure behind the wave will be equal to the new pressure level. The boundary condition for a wave reflecting from a surface will depend on whether the surface is "free" or constrained. The pressure behind a wave reflecting from a free surface will be equal to the pressure outside the free surface, while the velocity behind a wave reflecting from a constrained surface (such as the endwall) will be zero. The velocity behind a wave generated by the collision of a free surface with a constrained surface is also zero. These conditions are expressed below.

For a wave generated by a change in pressure at a boundary, or wave reflected from a free surface,

$$P_2 = P_{BOUNDARY} . \tag{4a}$$

For a wave reflected from a constrained surface, or a wave generated by collision of a free surface with a constrained surface,

$$V_2 = 0 . \tag{4b}$$

In the case of two pressure waves crossing each other, continuity and momentum equations are applied across each wave and are solved simultaneously for the conditions between the two waves.

In this analysis, the pressure waves generated are assumed to be weak; thus the velocity of the fluid is small compared to the speed of sound and the changes in density of the fluid are small compared with the initial fluid density. Thus, the wave speed may be expressed as follows;

$$c = \sqrt{E/\rho} . \tag{5}$$

III. WAVE MOTION ANALYSIS

Using the equations described above, the motion of the fluid as a function of time has been determined. In this section a description of the predicted fluid motion is given.

Fluid Motion as a Function of Time

The pressure step, which is applied to the lower surface of the fluid, generates a compression wave which begins to accelerate the fluid toward the cylinder endwall. After the fluid interface strikes the endwall, an additional pressure wave begins propagating throughout the fluid. Thus, a description of the fluid motion involves the tracking of these two pressure waves as they move throughout the fluid slug. It is useful, then, to separate the motion into two phases; the motion of the fluid before the collision of the free surface with the endwall, involving a single pressure wave, and the motion after the interface impacts on the endwall, involving the motion of two waves.

1. Fluid Motion Before Fluid Interface Hits Endwall

The application of the pressure step to the lower surface of the fluid generates a compression wave which propagates up the fluid slug at the speed of sound of the liquid, c. As shown in Figure 3, the fluid is motionless and at vacuum in front of pressure wave, while behind the wave the fluid is at pressure Po and moving upwards with velocity, Vo. (In Figures 3-11, compression and expansion waves are denoted by filled and unfilled arrows, respectively. The direction of the propagation of each wave is shown by the arrow.) The ratio of fluid velocity behind this wave, Vo, to the speed of sound, determined by application of the above equations, is approximately equal to the ratio of Po to the liquid bulk modulus.

$$Vo/c \simeq Po/E$$

Typically then, Vo will be three to ten percent of the speed of sound for this problem.

This compression wave will propagate up the fluid slug until it reaches the upper fluid surface, at which time it will reflect as an expansion wave traveling down the fluid at the speed of sound (Figure 4). Behind the expansion wave the fluid is moving upwards at velocity 2Vo and is at zero pressure. The expansion wave will propagate down the fluid until reaching the lower pressurized surface, reflecting as a compression wave, behind which the fluid will be moving upwards at velocity 3Vo (Figure 5). This wave will continue to propagate up and down the fluid slug with the velocity behind the wave increasing by Vo each time the pressure wave reflects from the upper or lower surface of the fluid.

At some time, however, the fluid interface, which begins moving after the initial arrival of the compression wave, will impact on the cylinder endwall, bringing the fluid locally to rest and generating an additional compression wave. The strength of this compression wave is dependent on the velocity of the fluid interface as it strikes the endwall, which increases by 2Vo each time the initial pressure wave reflects from the fluid interface. The velocity of the interface as it strikes the endwall will thus depend on the length of the cylinder, H, the length of the fluid slug, L, the speed of sound, c, the initial pressure, Po, and the bulk modulus, E. This relationship is shown nondimensionally in Figure 12 in terms of the fill ratio, which is the ratio of the length of the fluid slug to the length of the cylinder, and the ratio of initial pressure to bulk modulus.

Values of fill ratio and initial pressure to bulk modulus ratio which lie in region I represent cases where the initial pressure wave will reflect from the fluid interface only once before the interface impacts on the endwall. Thus, the velocity of the interface for these cases will be 2Vo. Values of fill ratio and initial pressure to bulk modulus ratio which lie in Region II, represent cases where the initial pressure wave will reflect twice from the fluid interface before the interface impacts on the endwall, yielding a interface velocity on impact of 4Vo. Points below region II represent cases where 3 or more reflections are expected. Typical fill ratios and initial pressure to bulk modulus ratios for the problem of interest lie in Region I; thus the examination of the fluid motion after the interface impacts on the endwall need only focus on the cases where the initial pressure wave reflects from the interface only once.

2. Fluid Motion After Fluid Interface Hits Endwall

For fill ratios and initial pressure to bulk modulus ratios of interest, then, the upper surface of the fluid will impact on the cylinder endwall after the arrival of the initial pressure wave, but before this pressure wave reflects from the lower surface of the fluid and returns. The collision of the fluid interface with the cylinder endwall will generate a secondary compression wave which travels down the fluid slug. Behind the secondary wave the fluid is brought to rest, doubling the pressure. The state of the fluid motion at this point in time is shown in Figure 6. (The primary wave is shown as a solid line, while the secondary wave is shown as a dashed line.) Both pressure waves move down the fluid slug until the primary wave reaches the pressurized surface and reflects as a compression wave, as shown in Figure 7. Behind this compression wave the fluid velocity is increased to 3Vo.

The crossing of the primary and secondary pressure waves, shown in Figure 8, causes the pressure between the two waves to increase to 3Po and the velocity to decrease to Vo.

The primary wave continues moving up and reflects as a compression wave after reaching the endwall. Between this compression wave and the endwall the pressure is increased to 4Po. The secondary pressure wave moves toward the pressurized surface and reflects as a expansion wave. The fluid behind this wave is now moving away from the endwall at velocity Vo. The fluid is now at the state shown in Figure 9.

The two pressure waves again cross, dropping the pressure between them to 2Po and causing the fluid between the two waves to move at 2Vo in the direction away from the endwall. This is shown in Figure 10.

The secondary pressure wave continues moving toward the endwall and reflects as an expansion wave, dropping the pressure between the endwall and the wave to vacuum. The primary wave also reaches the pressurized surface and reflects as an expansion wave, as shown in Figure 11. The pressure waves will continue to move throughout the fluid until they are damped out by viscous effects. (In this analysis there is no damping of the waves since viscous effects are neglected.) At this point the analysis is discontinued, because the maximum pressure at the endwall (4Po) has been relieved.

IV. RESULTS

Results for the pressure as a function of space and time are presented in nondimensional form. Endwall pressure as a function of time, again nondimensionalized, is examined and compared with an existing theory. Finally, dimensional results are presented for a typical case to provide insight into the physical problem of interest.

A. Pressure Time-Space Diagram

With the fluid motion defined over the time interval of interest, a plot of the pressure as a function of time and space can be constructed for a given fill ratio and initial pressure to bulk modulus ratio. Figures 13-16 show the pressure time-space diagram for a constant pressure to bulk modulus ratio (Po/E = .035) and for four different fill ratios of interest, .97, .95, .93, and .90. Figures 17-20 display the pressure time-space diagram for a single fill ratio (.95) and varying pressure to bulk modulus ratio, .025, .035, .05, and .10. Time has been nondimensionalized by the time required for a pressure wave to travel the length of the fluid slug. The vertical ordinate represents the axial position from the bottom cylinder nondimensionalized by the cylinder length. The pressure at a particular instant in time and at a particular axial position is represented by the shading at the appropriate location on the graph.

The position of the upper and lower fluid surfaces as a function of time are shown by the thickened lines on the upper and lower portions of the figures, while the position of the primary and secondary pressure waves are represented by the thin solid and dashed lines respectively.

These figures may be used to determine the pressure as a function of time at a particular axial position within the cylinder by drawing a horizontal line at the appropriate vertical ordinate on the graph. Similarly, the spacial distribution of pressure at a particular instant in time is represented by a vertical line at the appropriate horizontal ordinate.

Figure 13 displays the pressure history for what may be a typical case of interest; .97 fill ratio, Po of 241.0 MPa, and bulk modulus of 6895. MPa (water subject to a pressure of 689.5 MPa has a similar bulk modulus).[1] After the collision of the interface with the endwall, a region of pressure 2Po is seen to develop. This region extends over a large portion of the cylinder, from the endwall to the lower 30% of the cylinder. Adjacent to the region of 2Po are two regions of high pressure of magnitude 3Po and 4Po. The region of 4Po begins at the endwall after the collision of the primary wave with the endwall, and is seen to occur only in the top 25% of the cylinder. Nearly the entire length of the cylinder appears to experience a pressure of 3Po over a small period of time for this case.

The effect of changing the fill ratio is shown in Figures 13-16. Decreasing the fill ratio is seen to increase the duration and extent of the

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1. *C. Carmichael, "Kent's Mechanical Engineers' Handbook," Design and Production, Twelfth Edition, Wiley Handbook Series, 1964.*

region of pressure 4Po. At the fill ratio of 90% the region of 4Po extends over the upper 60% of the cylinder and lasts nearly four times longer than the adjacent region of 2Po at the endwall. Interestingly, the size of the region of pressure 3Po seems to increase with decreasing fill ratio until it reaches a maximum value, and then seems to decrease.

The effect of changing the ratio of Po to the bulk modulus while holding the fill ratio constant is shown in Figures 17-20. These figures demonstrate the effect of changing the initial pressure Po and/or changing the bulk modulus of the fluid.

In the case of changing the initial pressure Po, the duration and extent of the 4Po region is seen to decrease with increasing initial pressure. Thus, while the peak pressure on the endwall can be increased by increasing the initial pressure, the duration of this pressure will decrease somewhat.

Additionally, if the bulk modulus of the fluid is changed, this theory predicts that the duration of the peak pressure region will decrease as the bulk modulus is decreased (as the fluid is made more compressible), but the magnitude of the peak pressure will remain constant.

In Figures 13-20 the degree to which the fluid column is compressed is seen by comparing the initial length of the fluid column with the length at a later time. Compression of 10%-40% is seen and is reflective of the very high pressure levels which the fluid experiences.

B. Pressure on the Cylinder Endwall

The pressure on the endwall of the cylinder as a function of time is an item of significant interest in this project. These pressures, for the cases discussed above, have been taken from Figures 13-20 and replotted in Figures 21-28. Also displayed on these figures are the values determined by a previous theory.[2] In that analysis, the motion of the fluid slug was treated as a rigid body until it collided with the endwall. A pressure wave was then generated and traveled down the fluid slug. This resulted in a single pressure jump, to a maximum pressure which remained constant in time.

The endwall pressure, as predicted in the current analysis, is zero until the fluid interface collides with the endwall, increasing the pressure to 2Po as the secondary pressure wave is generated. The arrival of the primary wave at a later time increases the pressure further to 4Po. The endwall pressure is later relieved to vacuum as the secondary pressure returns.

Figures 21-24 show that decreasing the fill ratio increases the duration of the peak pressure 4Po substantially, while decreasing the duration of the 2Po pressure level. In contrast to the previously proposed theory which predicts a single jump in the endwall pressure whose magnitude is a function of the fill ratio, the current analysis predicts, for the fill ratios of

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2. *J. L. Watson, B. P. Burns, and J. M. Bender, "An Analysis of a Previously Unexplained Event (U)," U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, Maryland, ARBRL-MR-03227, November 1982 (CLASSIFIED).*

interest, a maximum pressure level (4Po) independent of fill ratio, but the duration which increases with decreasing fill ratio.

Figures 25-28 demonstrate the effect on the endwall pressure of changing the initial pressure to bulk modulus ratio. As was seen before, increasing the bulk modulus increases the duration over which the peak pressure of 4Po acts. Increasing the initial pressure Po will increase the peak endwall pressure proportionately, while decreasing the duration somewhat.

Interestingly, averaging the endwall pressure predicted by the current theory over the time where the endwall pressure is 2Po to 4Po yields a value similar to that predicted by the previous theory. This is because the rigid body assumption of the previous theory treats the motion of the fluid slug in global or average sense, while the current theory treats the motion more discretely. Correspondingly, these results indicate that the more compressible the fluid, the greater the difference in the predicted peak pressures between the two theories.

C. Dimensional Results for a Typical Case

In order to gain a better feeling for the magnitude of the physical variables of interest, endwall pressure as a function of time is presented for the following case.

H	= .67 m
E	= 6895 Mpa
Po	= 241 MPa
ρ	= 1000 kg/m^3
Fill ratio	= .95

Since the ratio of the initial pressure to the liquid bulk modulus is .035 and the fill ratio is .95, the results for one of the cases obtained previously (Figure 26) may be applied. The dimensionalized result for endwall pressure as a function of time for this case is shown in Figure 29. As before, the pressure first jumps to twice the value (482 MPa) of the initial pressure step before jumping to the four times (964 MPa) the initial pressure value. The time over which the pressures 2Po and 4Po act are .3 and .17 milliseconds, respectively, and the entire process is completed in about 1. millisecond.

V. CONCLUSIONS

The results of this analysis provide significant insight into the physical processes which may occur in a liquid-filled shell subject to large initial pressures, and stress the importance of modeling the compressibility of the fluid within the shell for the current problem of interest.

The motion of the fluid is driven by two pressure waves, one generated by the initial pressure step and another generated by the collision of the fluid with the endwall. The highest pressure levels occur for a longer duration near the top of the cylinder. The theory predicts that decreasing the fill ratio will increase the duration of the peak pressure at the endwall but not

the magnitude for the range of fill ratios and initial pressure to bulk modulus ratios currently of interest. This peak pressure will be four times the value of the initial pressure step. The analysis indicates that peak pressures greater than four times the initial pressure step are possible for fill ratios less than the values currently of interest. Increasing the magnitude of the initial pressure step will increase peak pressure proportionately, but the duration over which this peak pressure acts will be decrease slightly. Decreasing the bulk modulus of the fluid (i.e. making the fluid more compressible) will cause the duration of peak pressure to increase slightly.

It is acknowledged that this analysis does not model such effects as area change within the shell, changes in bulk modulus with pressure, and variation in the pressure at the lower surface of the fluid with time. The modeling of these effects is probably more suitably handled by numerical techniques. As this analysis has demonstrated, the numerical technique chosen should model the compressible nature of the fluid and have the capability to track moving pressure waves.

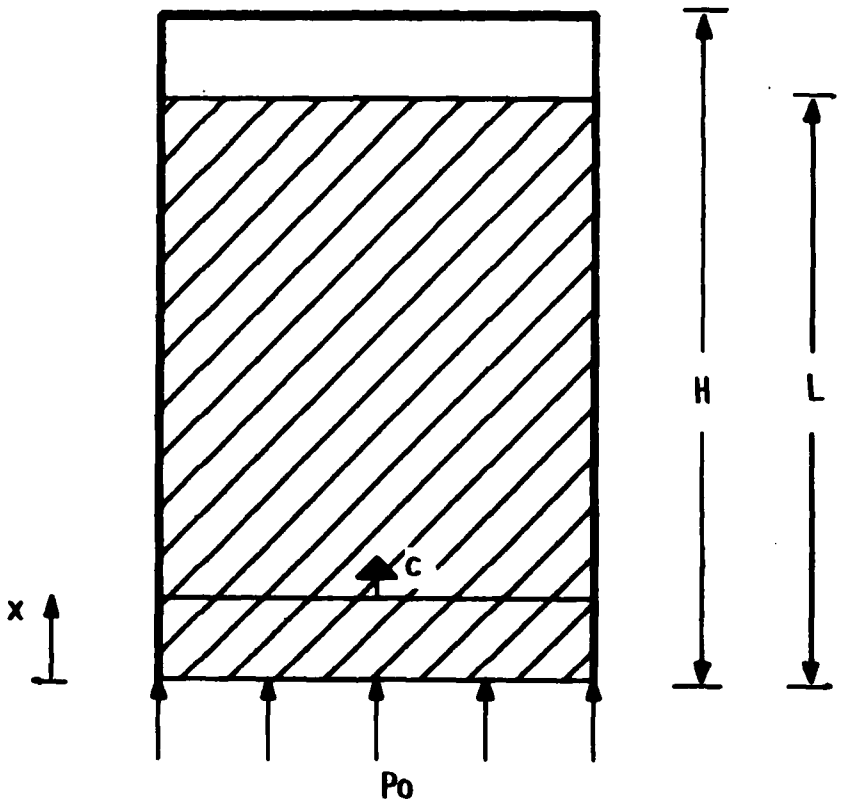

Figure 1. Setup for Idealized Problem

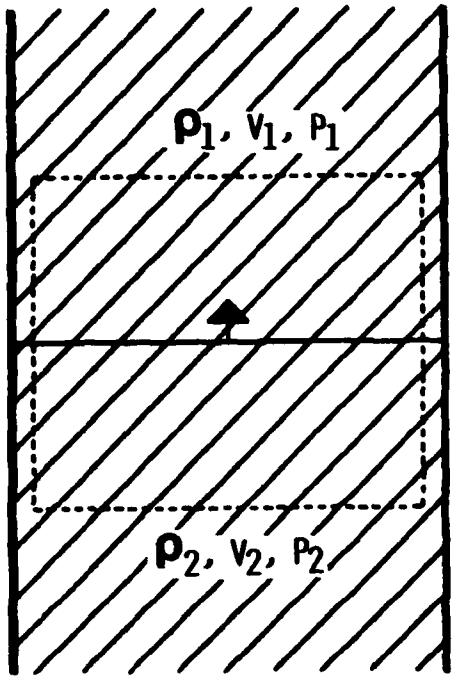

Figure 2. Control Volume for Solution of Mass and Momentum Equations

PRESSURE STEP IS APPLIED TO FLUID.

PRIMARY PRESSURE WAVE PROPAGATES

UP THE FLUID SLUG.

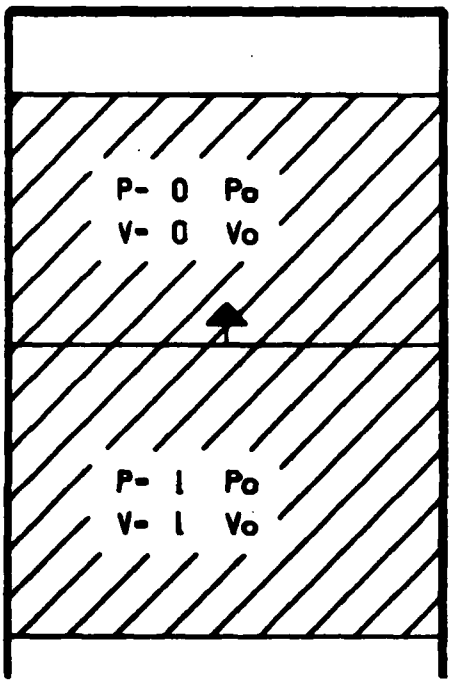

Figure 3. Propagation of Initial Pressure Wave

PRIMARY PRESSURE WAVE REACHES FLUID INTERFACE AND RETURNS AS AN EXPANSION WAVE.

INTERFACE BEBINS TO MOVE TOWARD ENDWALL.

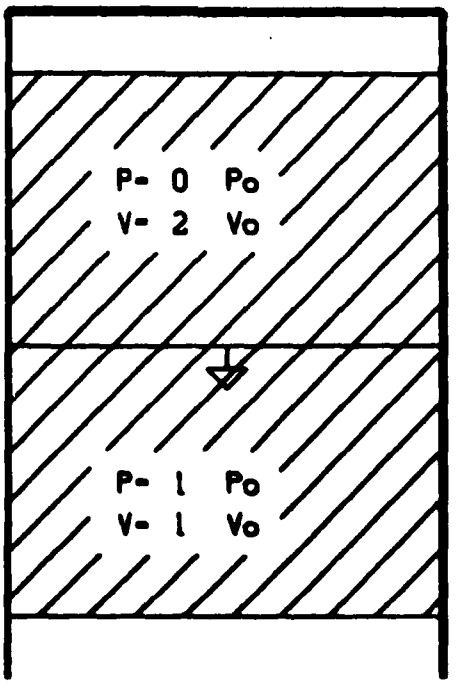

Figure 4. Reflection of Initial Pressure Wave from Liquid Interface

PRIMARY PRESSURE WAVE REACHES

PRESSURIZED SURFACE AND REFLECTS

AS A COMPRESSION WAVE.

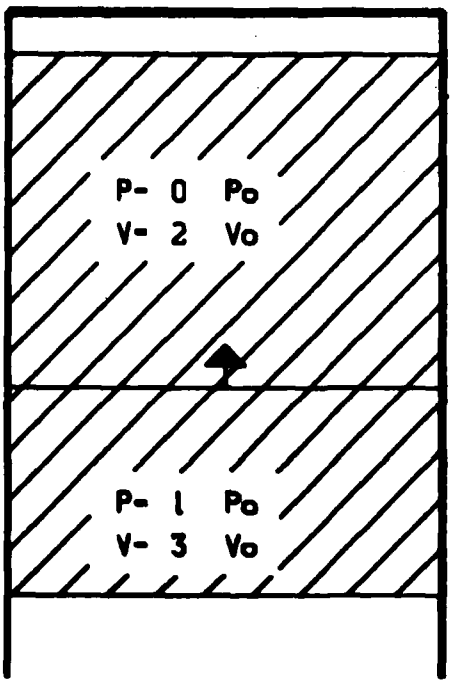

Figure 5. Reflection of Initial Pressure Wave from Pressurized Surface

FLUID INTERFACE COLLIDES WITH ENDWALL

AND GENERATES A SECONDARY COMPRESSION

WAVE THAT TRAVELS DOWN FLUID SLUG.

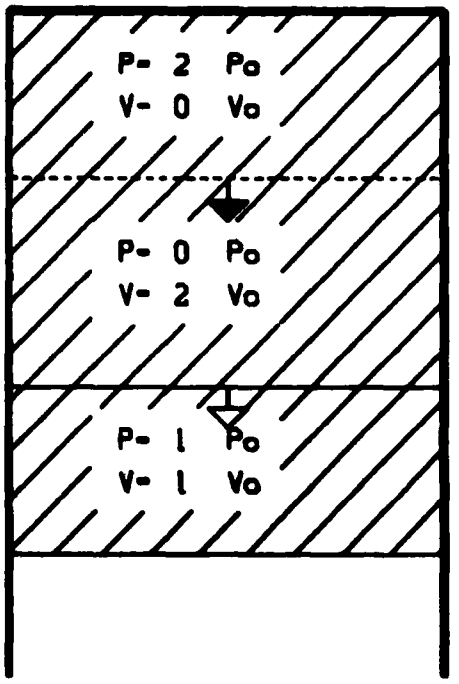

Figure 6. Generation of Secondary Pressure Wave by Collision of Interface with the Endwall

EXPANSION WAVE REACHES PRESSURIZED SURFACE AND BEGINS MOVING TOWARD ENDWALL AS A COMPRESSION WAVE.

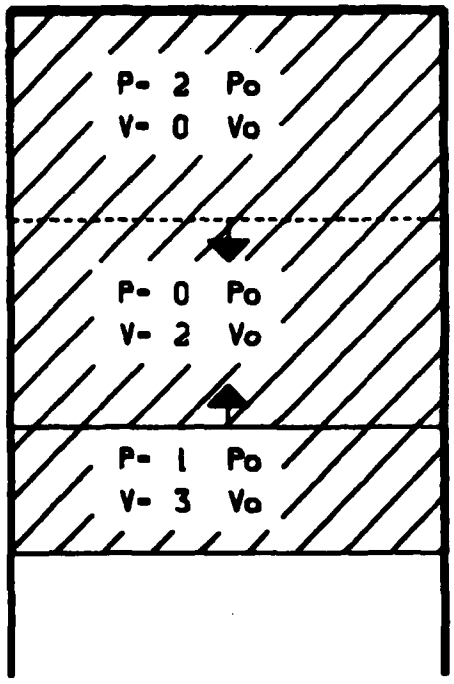

Figure 7. Reflection of Primary Pressure Wave from Pressurized Surface

PRIMARY AND SECONDARY COMPRESSION

WAVES CROSS.

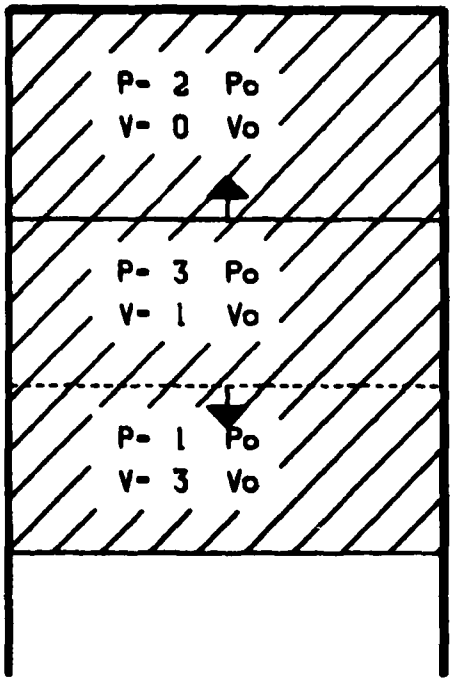

Figure 8. First Crossing of Primary and Secondary Pressure Waves

PRIMARY COMPRESSION WAVE REACHES ENDWALL AND REFLECTS AS A COMPRESSION WAVE. MAXIMUM PRESSURE OBTAINED ON ENDWALL. SECONDARY COMPRESSION WAVE REACHES PRESSURIZED SURFACE AND REFLECTS AS AN EXPANSION WAVE.

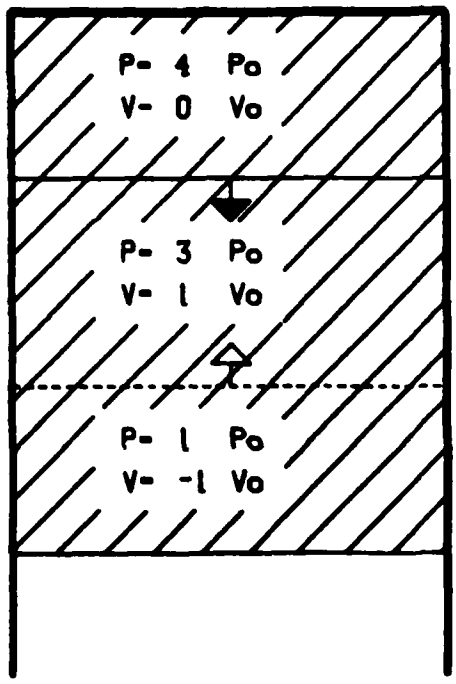

Figure 9. Reflection of Primary and Secondary Wave from Upper and Lower Surfaces

PRIMARY COMPRESSION WAVE AND SECONDARY

EXPANSION WAVE CROSS.

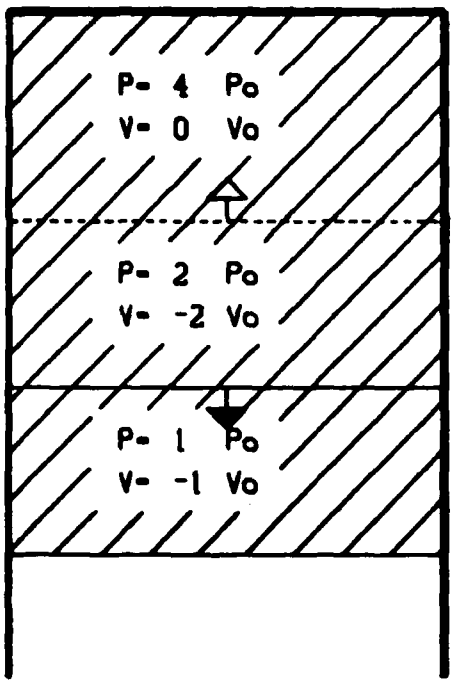

Figure 10. Second Crossing of Primary and Secondary Pressure Waves

PRIMARY WAVE REACHES PRESSURIZED SURFACE AND RETURNS AS AN EXPANSION. HIGH PRESSURE ON ENDWALL RELIEVED. SECONDARY EXPANSION WAVE REACHES ENDWALL AND REFLECTS AS AN EXPANSION WAVE.

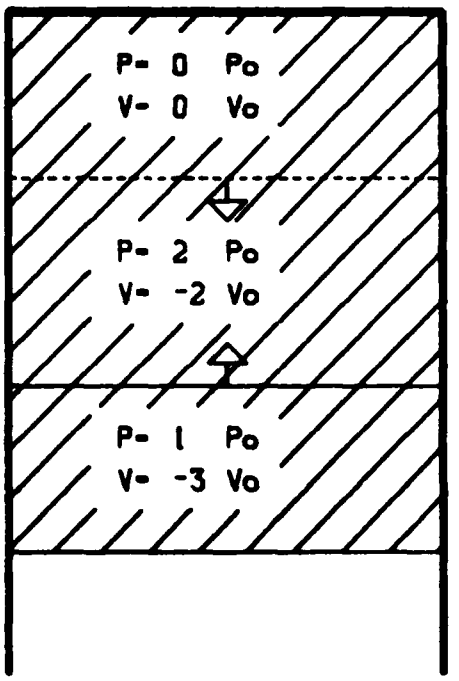

Figure 11. Reflection of Primary and Secondary Waves from Lower and Upper Surfaces

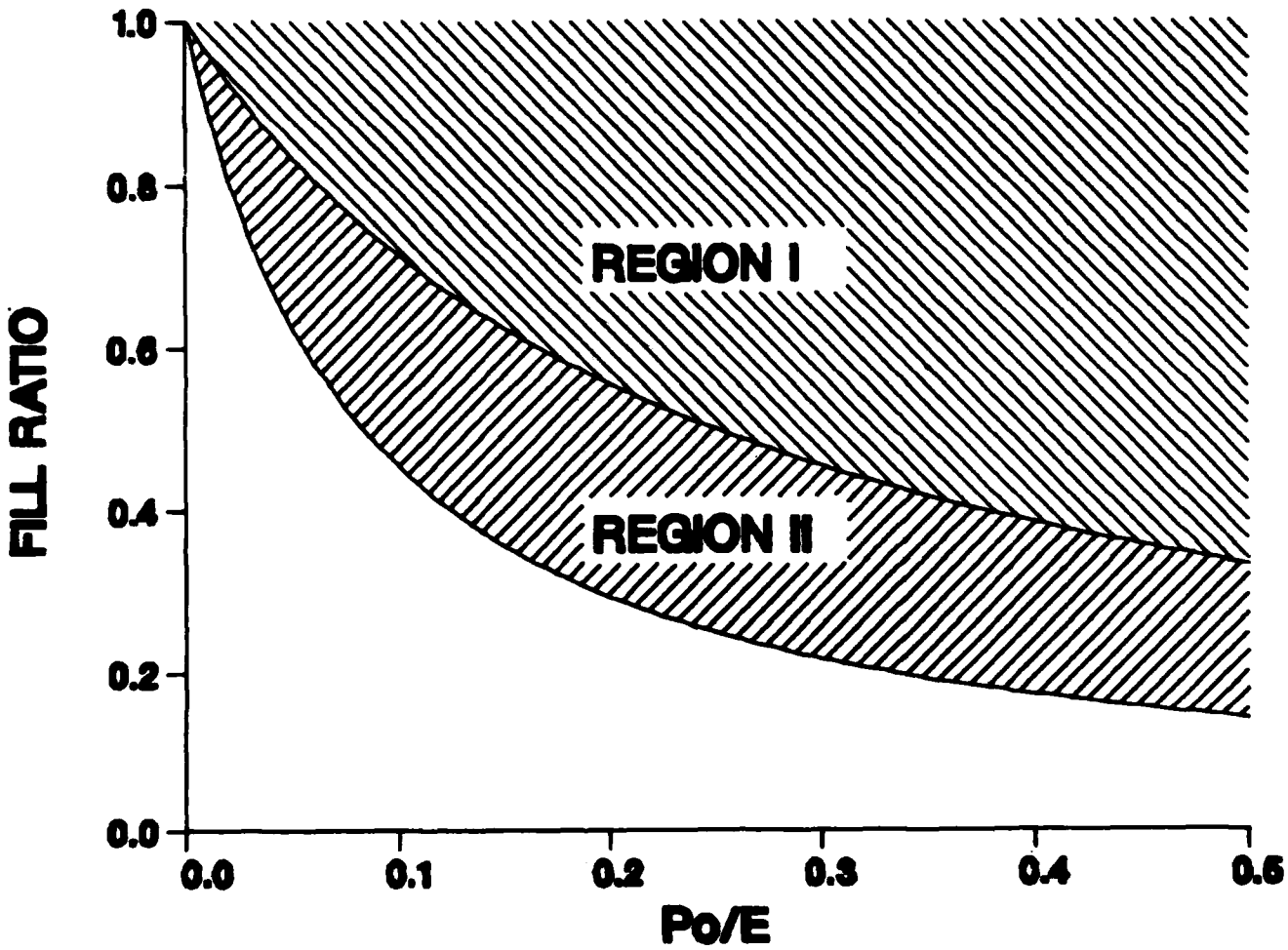

Figure 12. Wave Status When Interface Impacts on Endwall

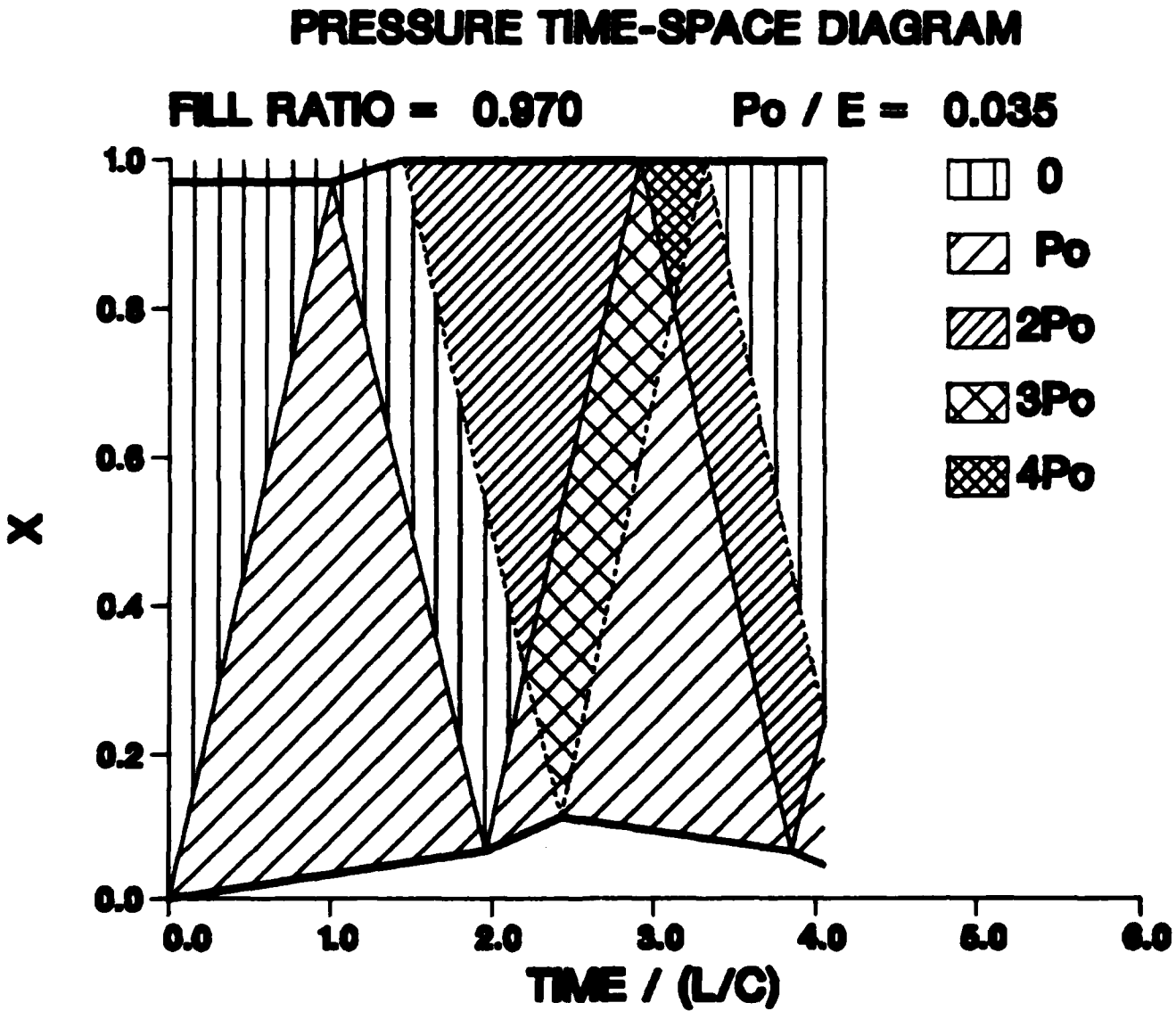

Figure 13. Pressure Time-Space Diagram, Fill Ratio = .97, Po/E = .035

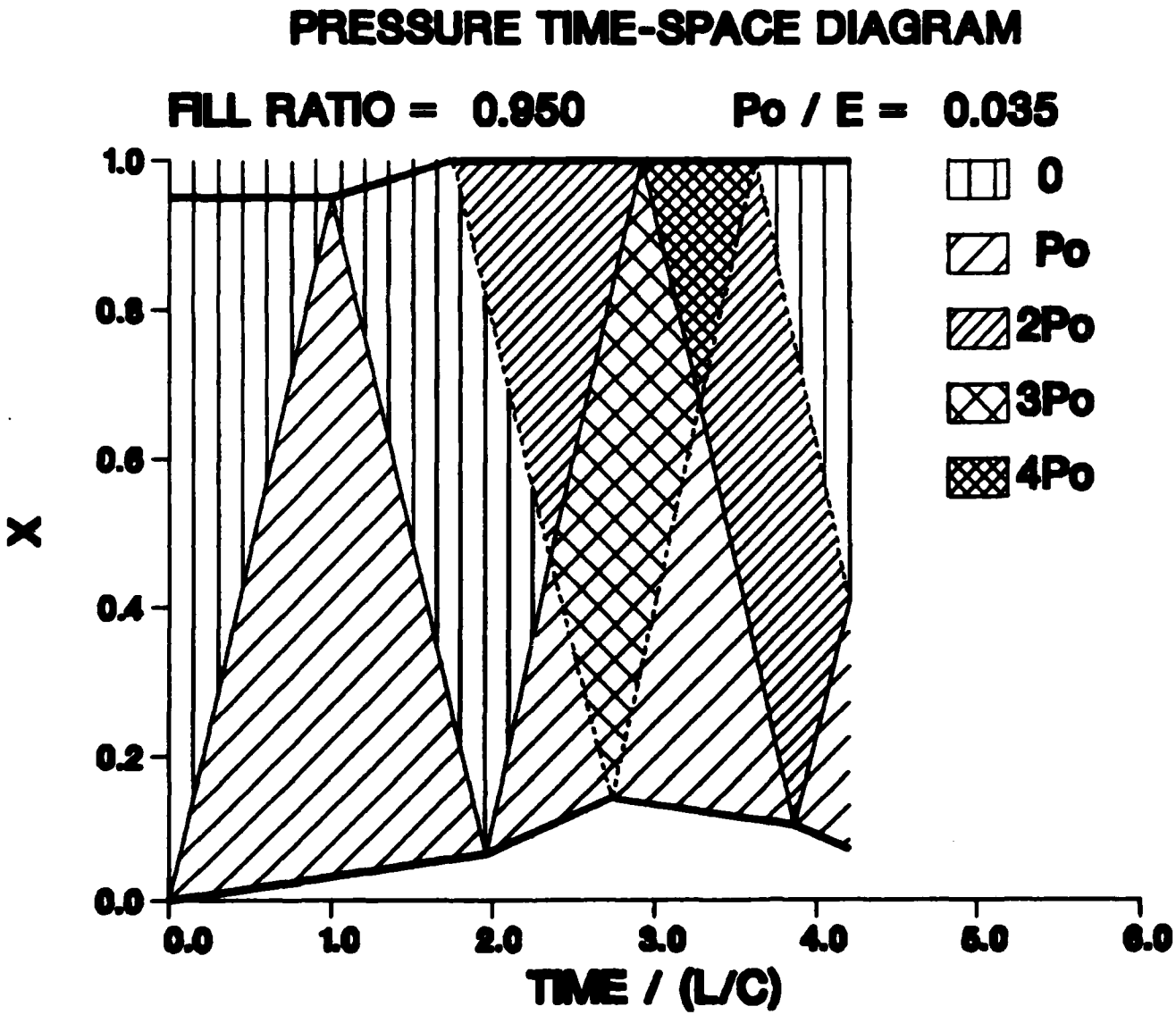

Figure 14. Pressure Time-Space Diagram, Fill Ratio = .95, Po/E = .035

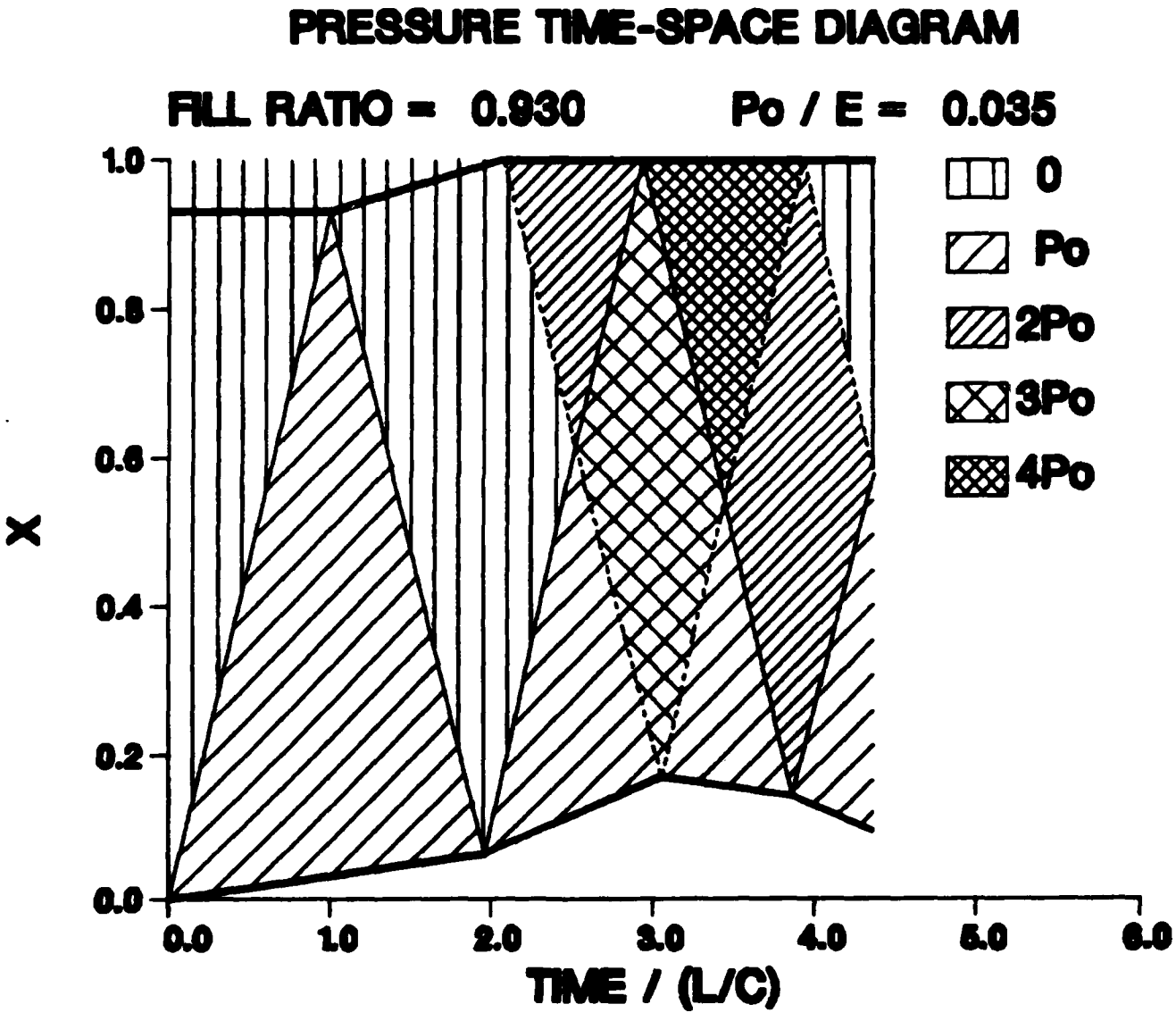

Figure 15. Pressure Time-Space Diagram, Fill Ratio = .93, Po/E = .035

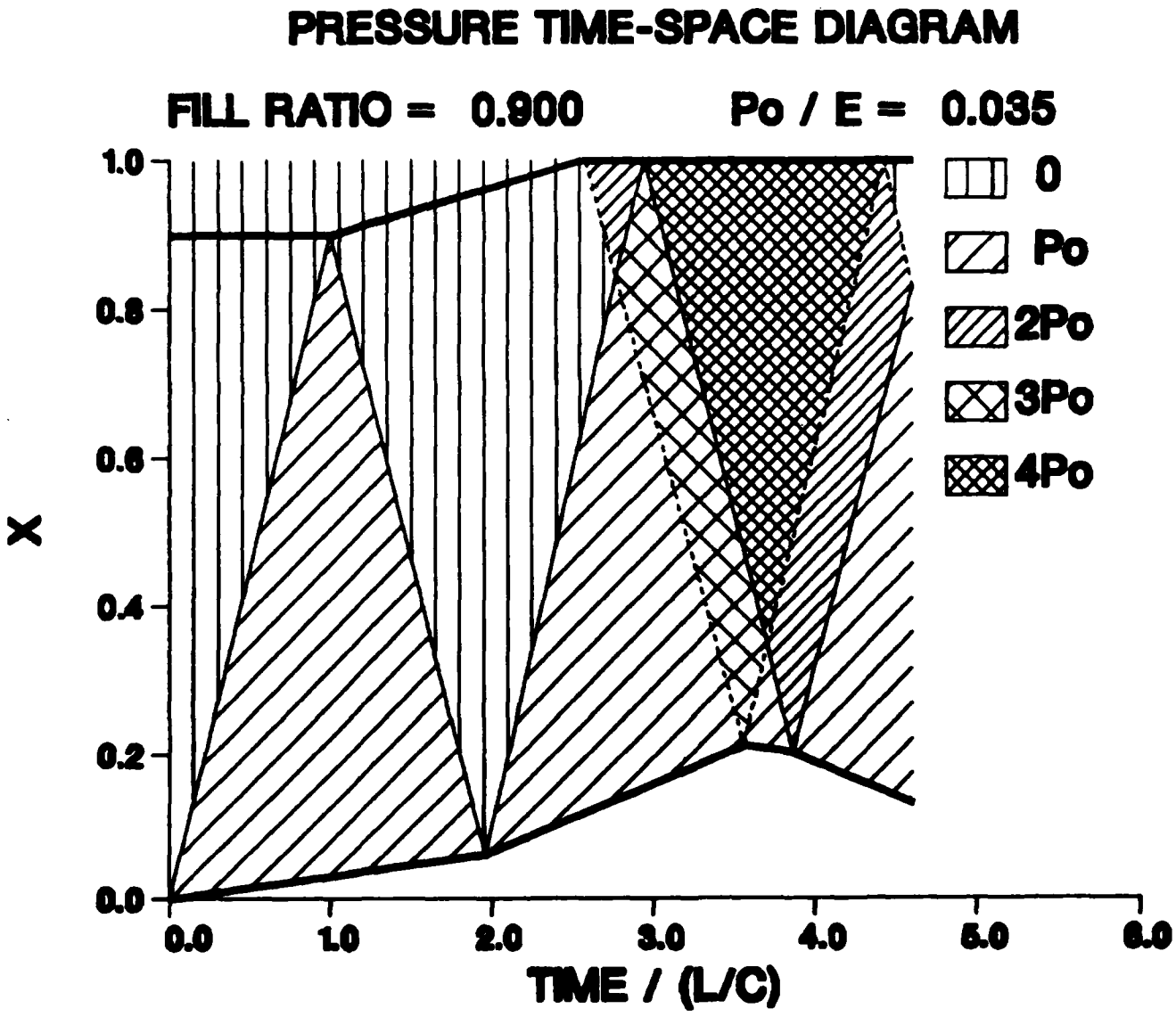

Figure 16. Pressure Time-Space Diagram, Fill Ratio = .90, Po/E = .035

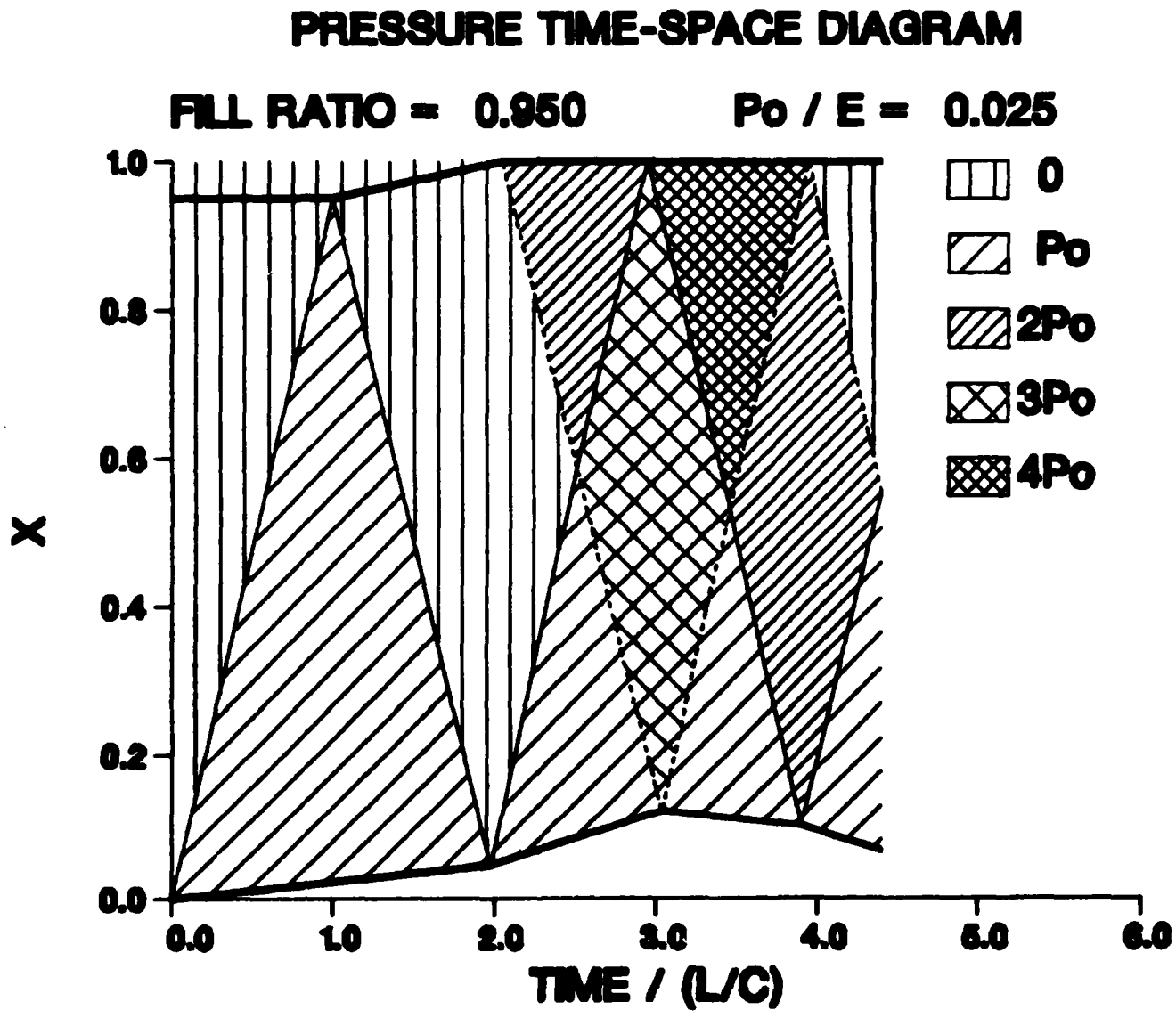

Figure 17. Pressure Time-Space Diagram, Fill Ratio = .95, Po/E = .025

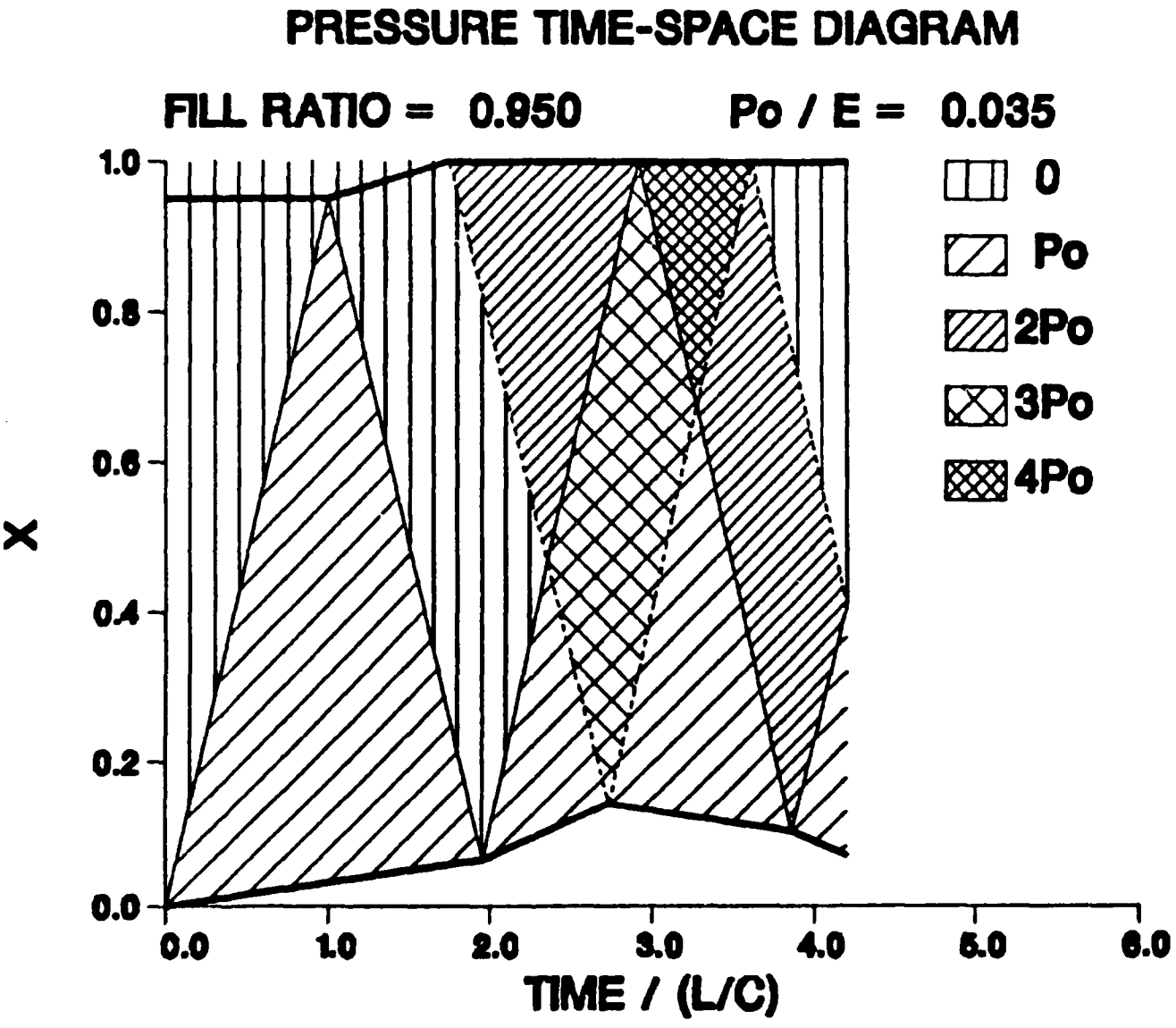

Figure 18. Pressure Time-Space Diagram, Fill Ratio = .95, Po/E = .035

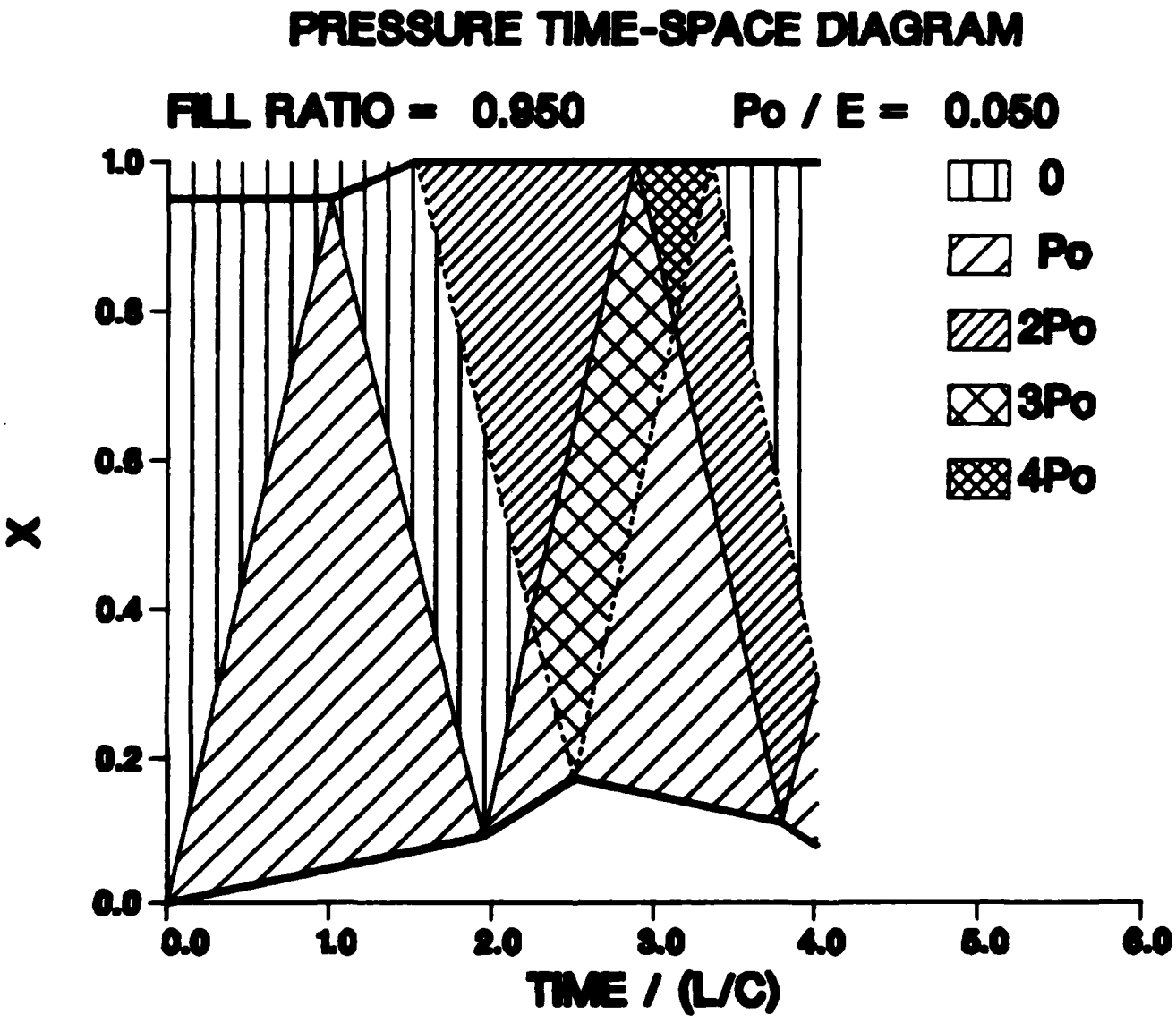

Figure 19. Pressure Time-Space Diagram, Fill Ratio = .95, Po/E = .05

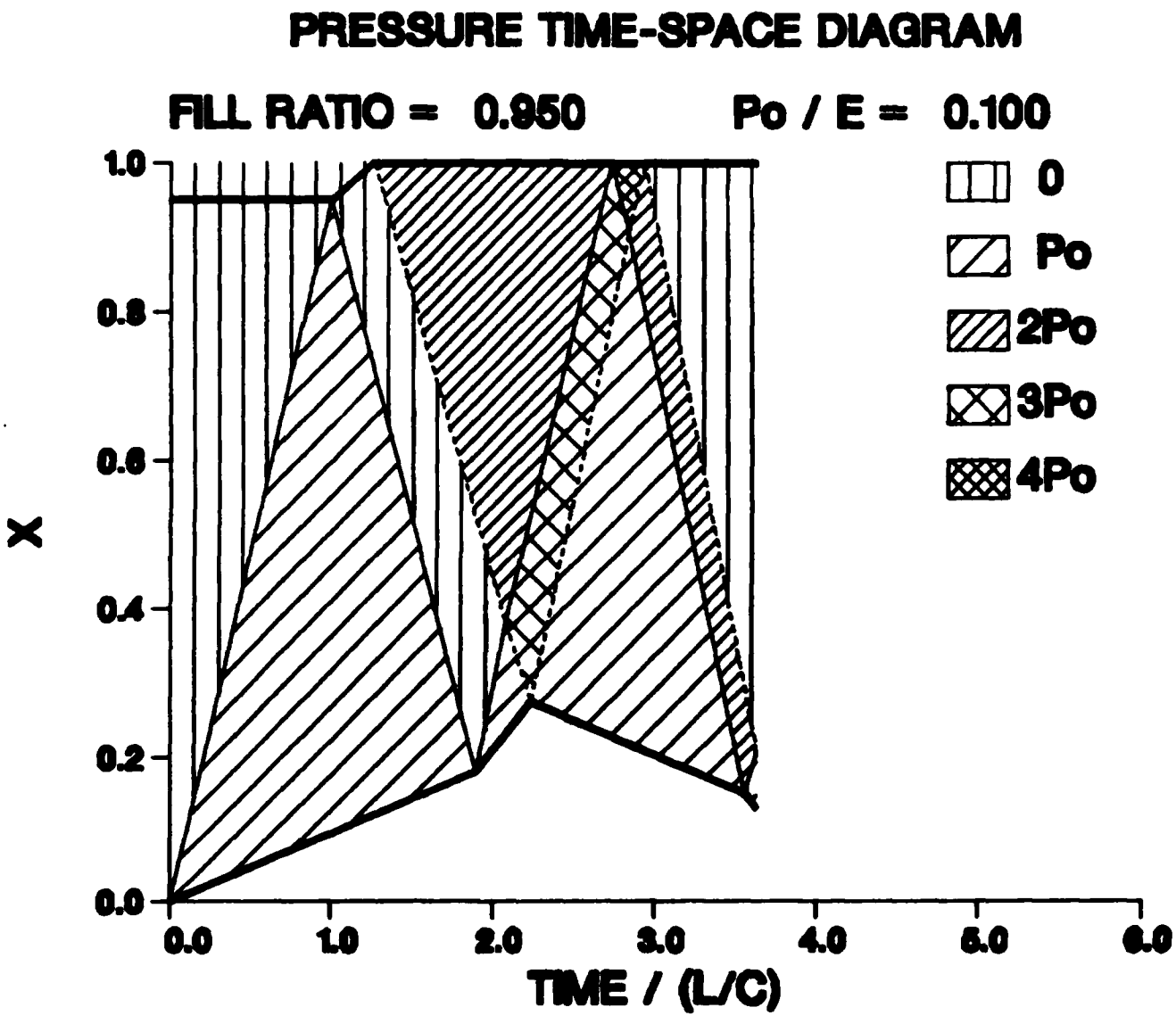

Figure 20. Pressure Time-Space Diagram, Fill Ratio = .95, Po/E = .10

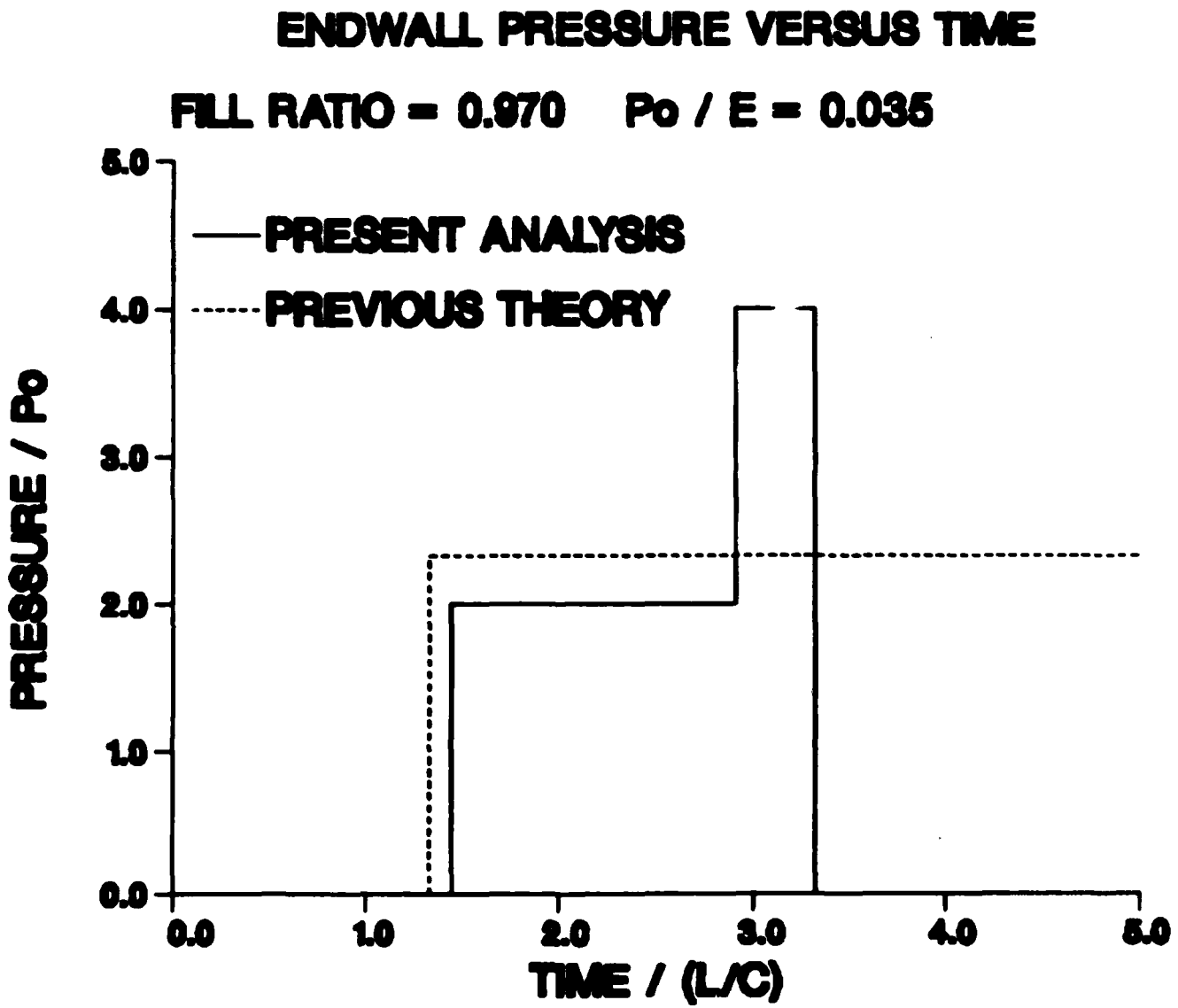

Figure 21. Endwall Pressure versus Time, Fill Ratio = .97, Po/E = .035

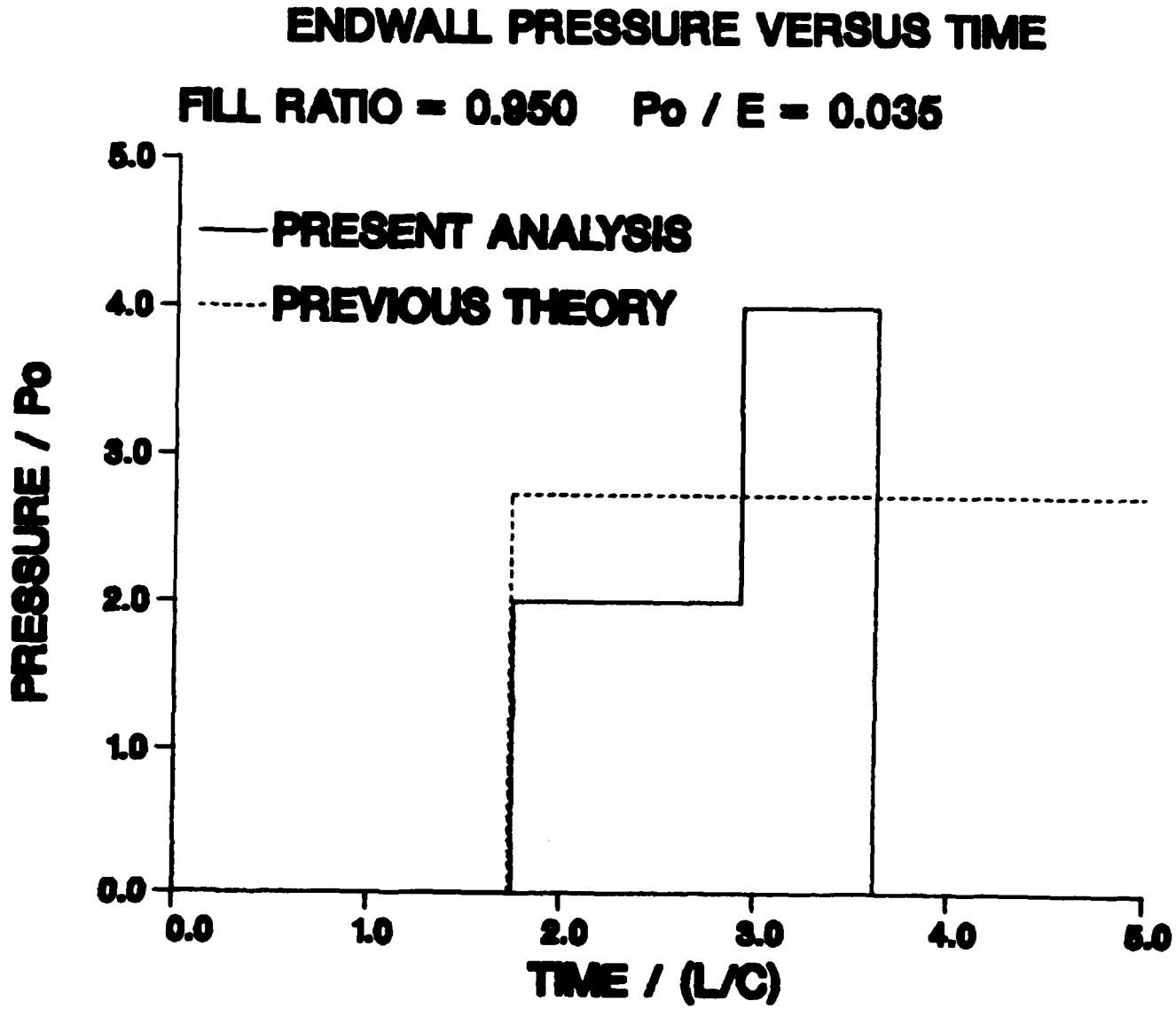

Figure 22. Endwall Pressure versus Time, Fill Ratio = .95, Po/E = .035

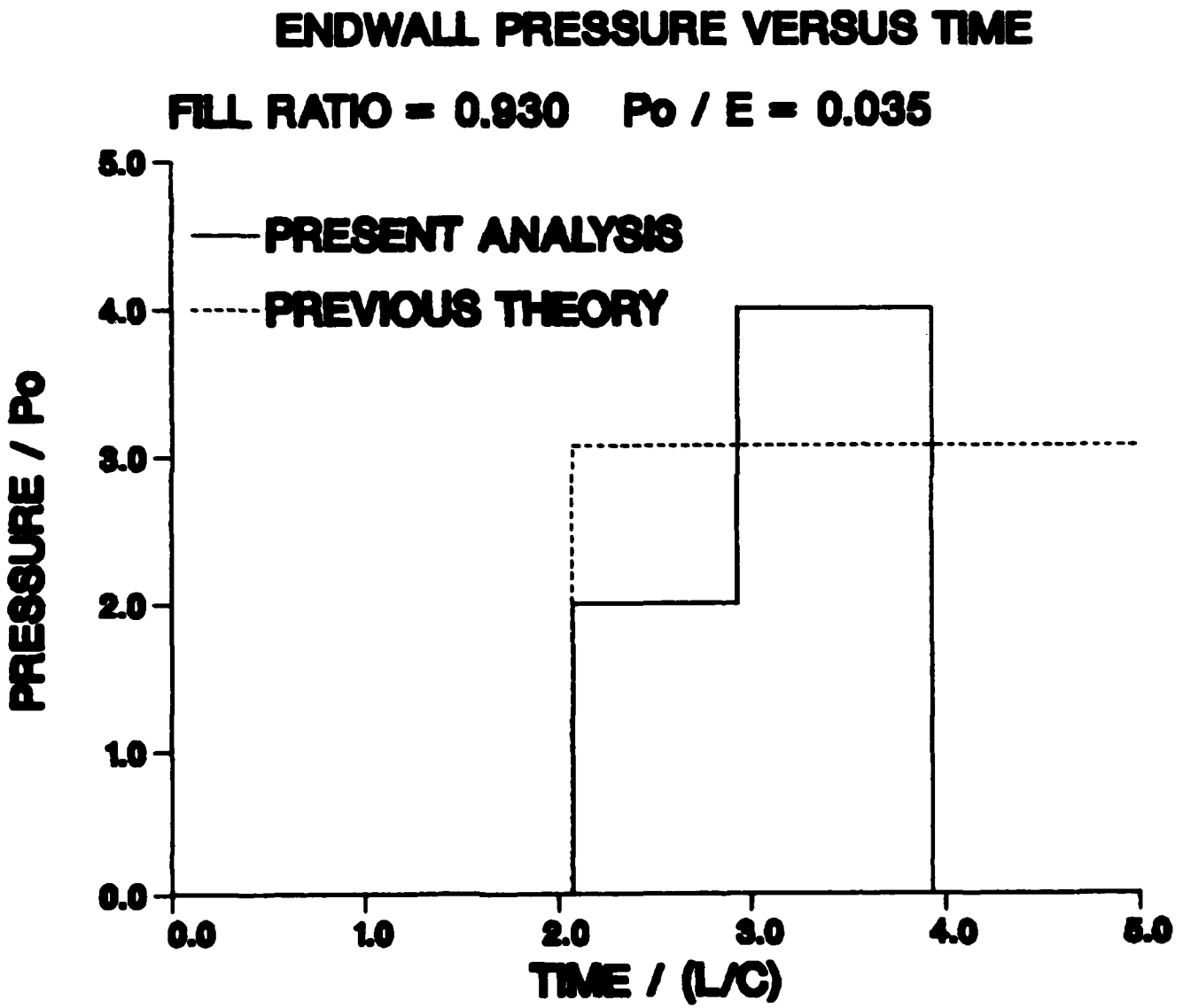

Figure 23. Endwall Pressure versus Time, Fill Ratio = .93, Po/E = .035

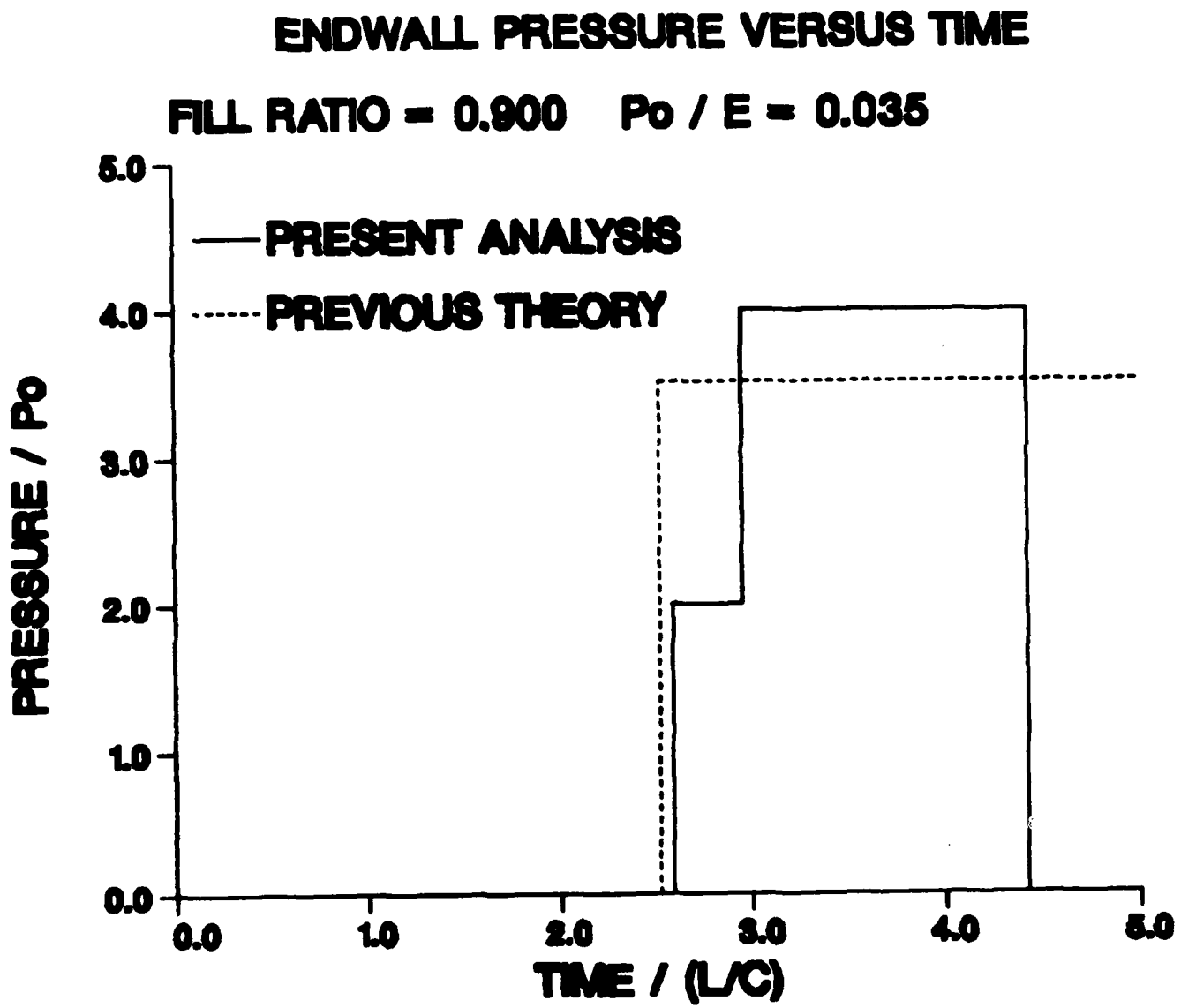

Figure 24. Endwall Pressure versus Time, Fill Ratio = .90, Po/E = .035

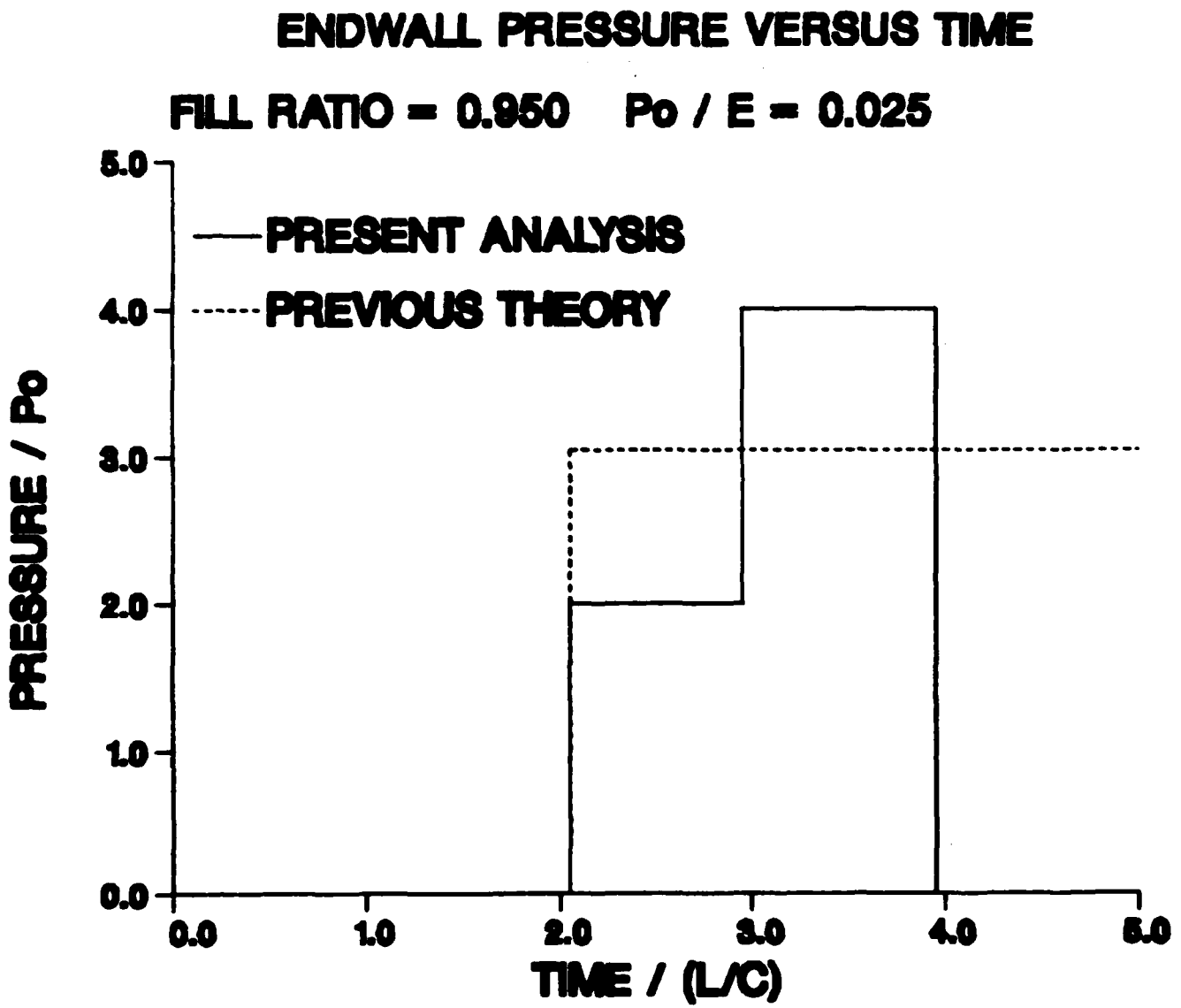

Figure 25. Endwall Pressure versus Time, Fill Ratio = .95, Po/E = .025

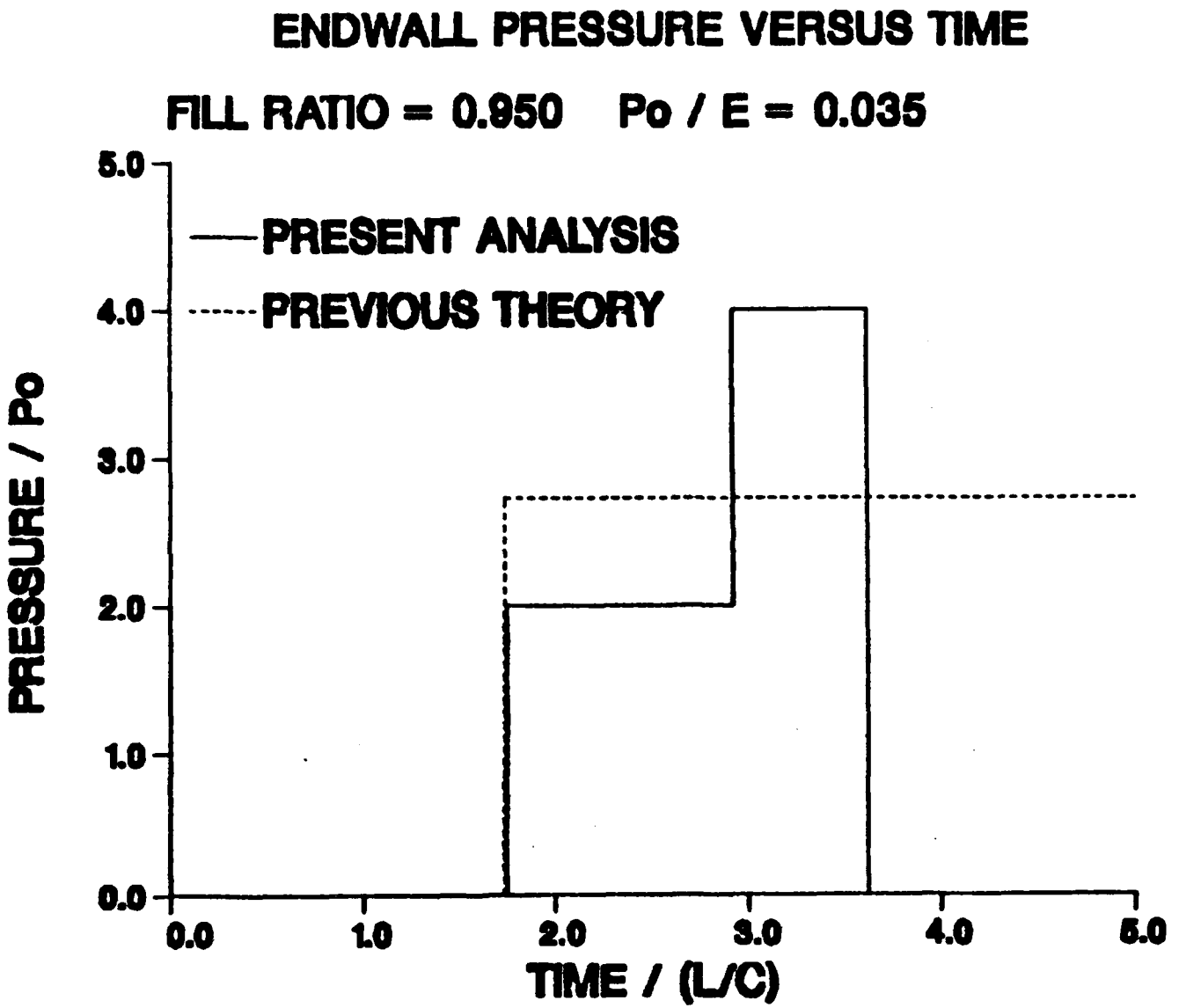

Figure 26. Endwall Pressure versus Time, Fill Ratio = .95, Po/E = .035

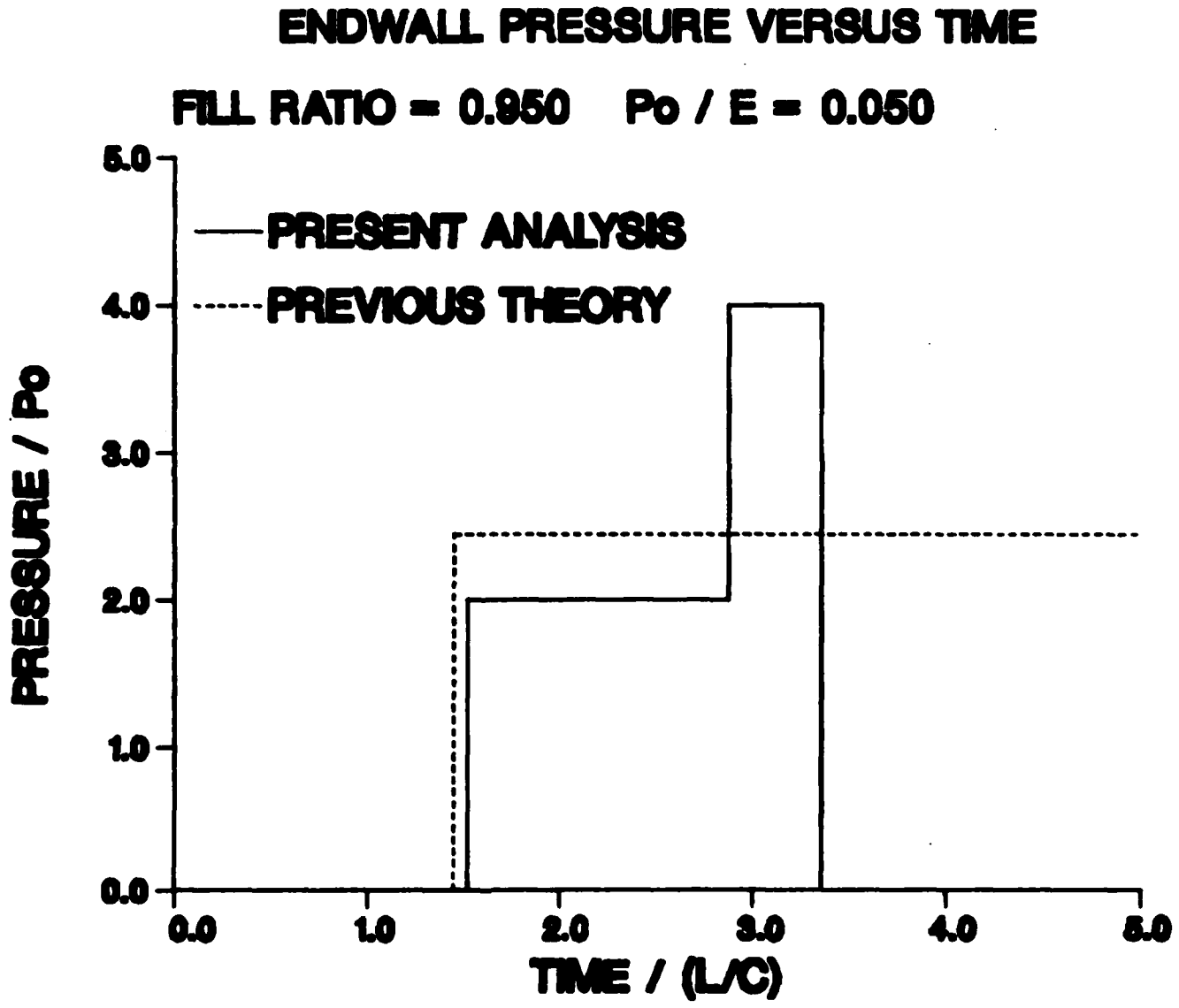

Figure 27. Endwall Pressure versus Time, Fill Ratio = .95, Po/E = .05

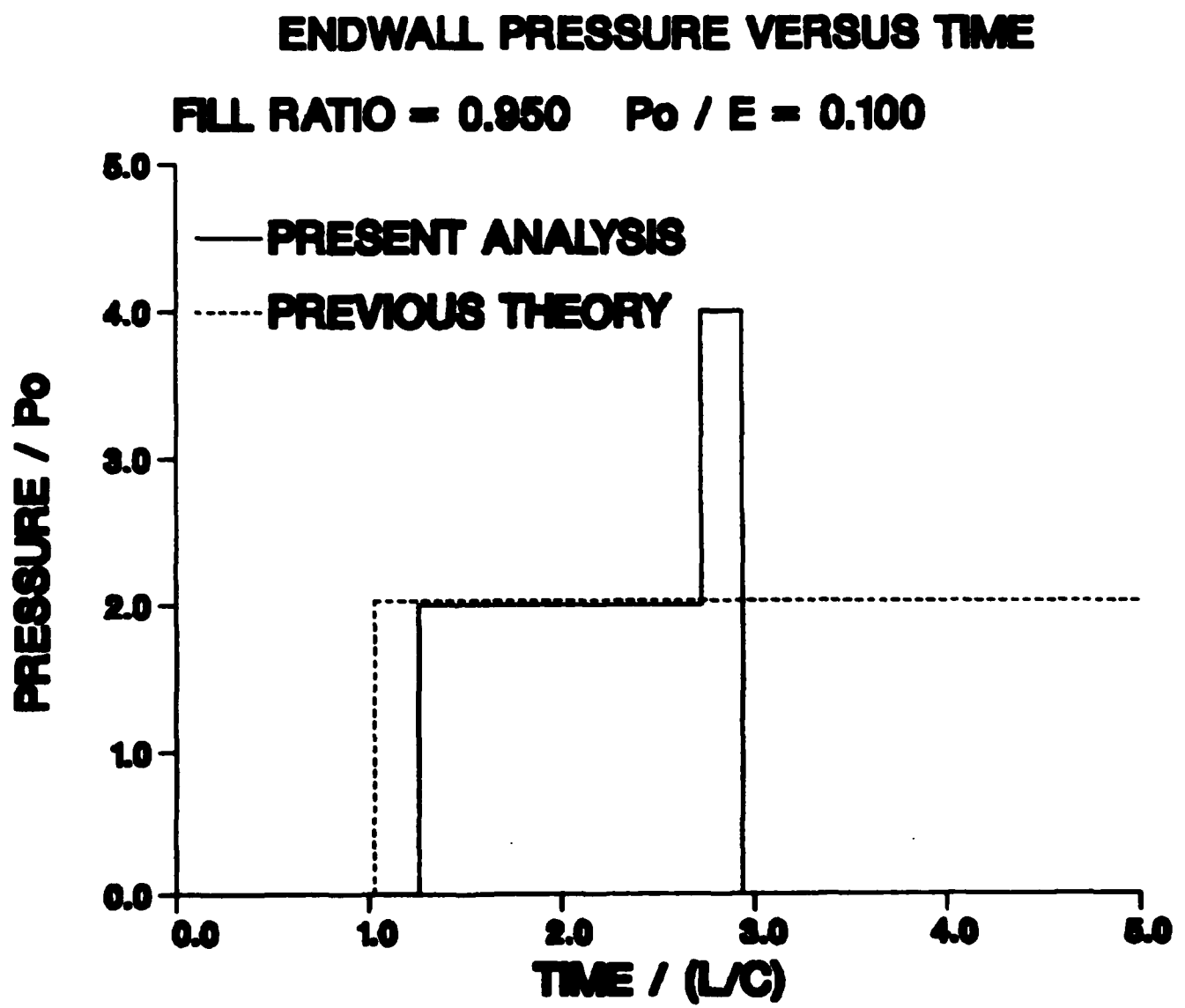

Figure 28. Endwall Pressure versus Time, Fill Ratio = .95, Po/E = .10

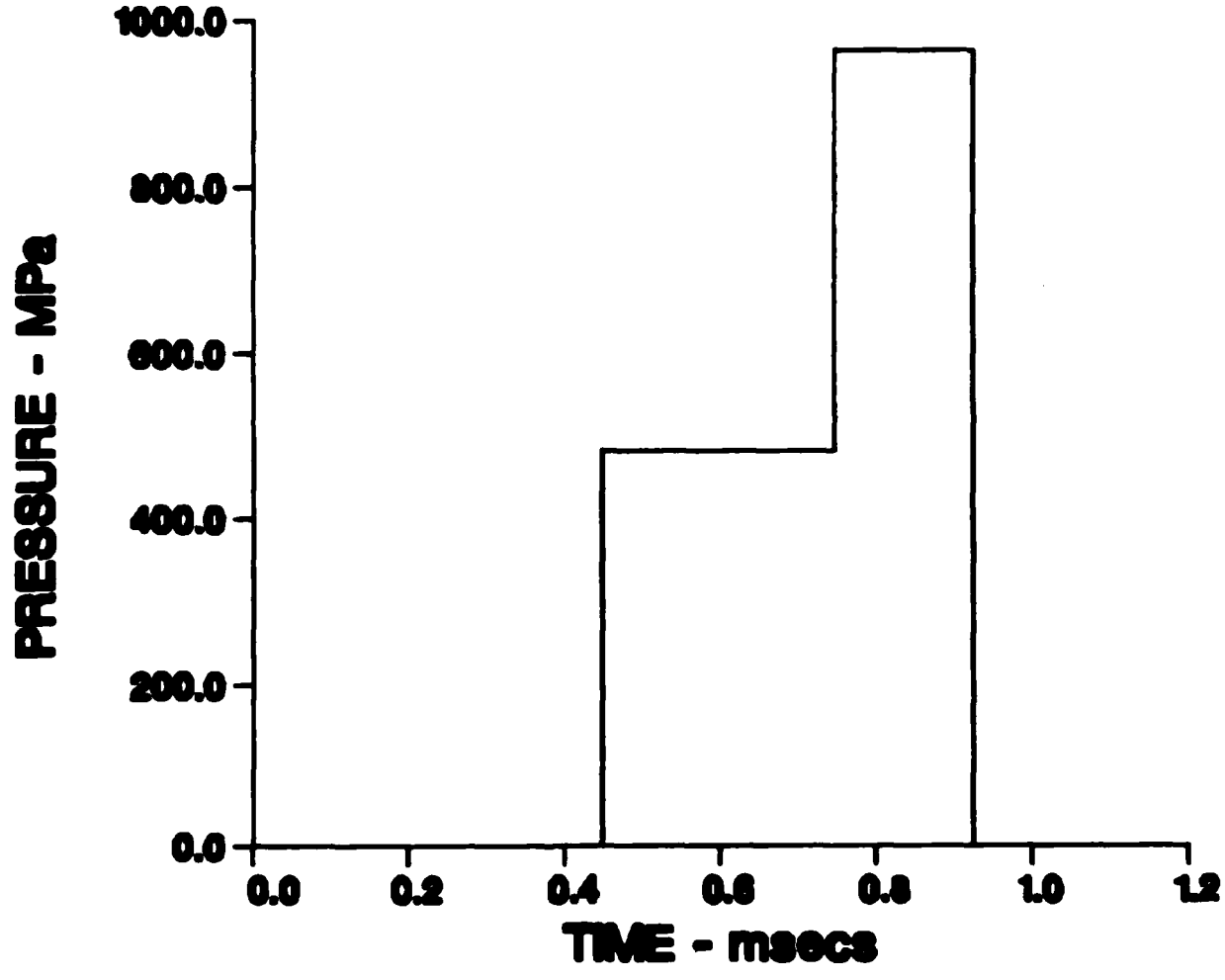

Figure 29. Endwall Pressure versus Time, Dimensional Result

LIST OF SYMBOLS

c	speed of sound in fluid, m/s
E	bulk modulus of fluid, N/m^2
L	length of fluid slug, m
H	length of cylinder, m
P	local pressure, N/m^2
$P_{BOUNDARY}$	pressure at liquid interface, N/m^2
Po	magnitude of initial pressure step, N/m^2
V	local velocity, m/s
Vo	velocity behind initial compression wave, m/s
x	nondimensional distance from bottom of cylinder, m
x'	distance from bottom of cylinder, m
ρ	local fluid density, kg/m^3

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